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(GR-GFZ-AOD-0001)

Gravity Recovery and Climate Experiment

AOD1B Product Description Document for Product Release 05

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Document Change

Issue	Date	Pages	Description of Change
Draft	22.09.2003	all	First version
1.0	22.10.2003	all	Included GRACE project comments on draft version
2.0	20.09.2005	6	Added changes w.r.t release 03 (substitution of the barotropic ocean model PPHA by the baroclinic model OMCT)
		7	Updated description of the necessary ECMWF forcing fields
		16	Added description of OMCT model to chapter 2.2.3
		21	Added processing strategy of OMCT to chapter 3.1
		28	Updated chapter 3.3 on mean fields
		32	Defined new chapter 4 (Available Releases)
		33	Updated chapter 5(Validation of AOD product)
		37	Chapter 6.2: Added remark that OCN1B read s/w is available at the archives
		39	Added OMCT references to Chapter 7
		40	Updated Chapter 8 (Abbreviations)
			Deleted appendix
2.1	04.11.2005	22	Corrected explanation to equation 3-3
		23	Corrected explanation to equation 3-5
		25	Corrected first sentence after figure 3-3
		26	Corrected explanation to equation 3-20
		27	Corrected last sentence of 3.2.2.1
2.2	26.04.2006	32	Updated RL03 availability period
		33	Changed title of Chapter 5 and included recommendation for TN04
		34	Changed title of Chapter 6
		36	Added comment on OCN1B availability
		38	Included new Chapter 7 “Average of AOD1B products: GAA, GAB and GAC”.
3.0	23.02.2007		Included RL04 relevant issues in Chapters 4-7, added clarification and recommendation on use of different products.
3.1	13.04.2007		Added clarifications in Chapter 6 and 7 for AOD1B “oba” data type and GAD products.
4.0	15.07.2013		Thoroughly revised and shortened version that isfocused entirely on the latest product release 05.
4.1	07.04.2014		Included new Chapter 3.7 “Discontinuities in atmospheric pressure data and associated correction products GAE and GAF”

1. Introduction

1.1 Outline

This version of the Product Description Document for the GRACE Atmosphere and Ocean Level-1B De-Aliasing (AOD1B) Product is dedicated to release 05. For previous releases 01 to 04 we refer to revision 3.1 of this document that is still available from the GRACE archives at ISDC and PO.DAAC.

Following some introductory information in chapter 1, the second chapter describes the required meteorological input data and the OMCT ocean model. In chapter 3, the processing strategy to derive atmospheric and oceanic pressure variations is described that considers the vertically varying atmospheric density and computes gravity coefficients by spherical harmonic analysis. The mean atmosphere and ocean fields, needed to derive residual mass variations, are described as well as the combination of the atmospheric and oceanic contributions. Chapter 4 gives more detailed comments on previous versions of AOD1B, whereas in chapter 5 the format and components of the AOD1B RL05 product are explained. The document is supplemented by a list of references and abbreviations.

1.2 High-Frequency Non-Tidal Mass Variability

Gravity field determination from low Earth-orbiting satellites is generally affected by time-changes in the external gravitational field and its underlying mass distribution within the atmosphere, at the surface, and in the Earth's interior. Due to sampling limitations of all satellite missions, observations are typically accumulated over a certain time-period in order to be able to solve for a global gravity field solution with reasonably high spatial resolution. For the GRACE mission, typical accumulation times range between 7 and 30 days.

Besides tidal signals that are present in the oceans and the solid Earth, there are also substantial non-tidal mass variations at periods below 30 days that take place at the Earth's surface. Evolving synoptic weather systems with horizontal dimensions of several ~100 km that are adverted with the mean flow cause surface pressure changes of a few ~10 hPa in middle latitudes. Heavy precipitation events associated with convective processes cause rapid increases of the amount of water stored on the continents, and winds associated with cyclonic pressure systems cause re-distributions of oceanic water masses, and thus changes in ocean bottom pressure.

Failures during accounting those high-frequency signals within the gravity field estimation process cause aliasing into the estimated gravity fields, a process that is at least partly responsible for the systematic meridional striations common to all GRACE gravity field solutions. Although these high-frequency variability is also affecting gravity field modeling from CHAMP and, less pronounced, from GOCE satellite observations, the GRACE mission, dedicated to the observation of time-variable mass transport phenomena, is affected most up to intermediate spatial wavelengths of several ~100 km (Fig. 1-1).

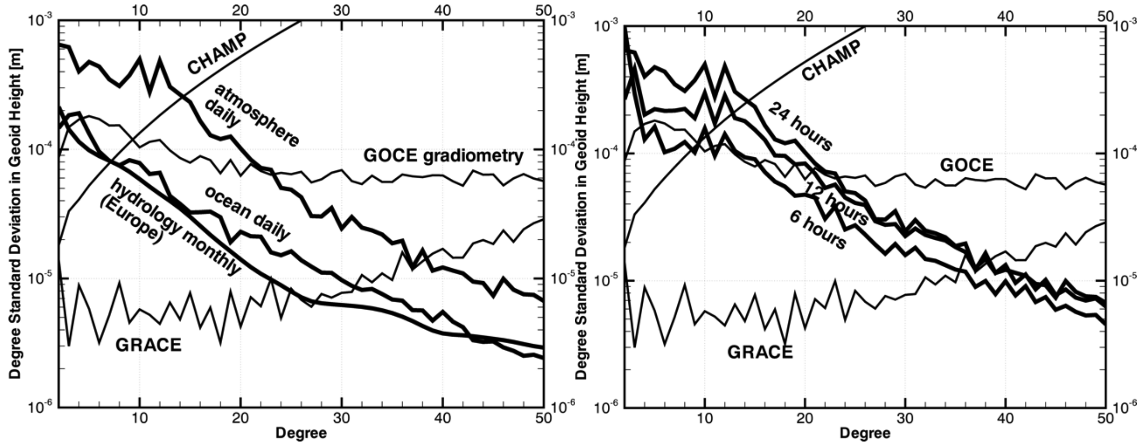

Figure 1-1: Gravity variation signals from atmosphere, oceans and terrestrial stored water in different time scales compared to mission sensitivities of CHAMP, GRACE and GOCE: daily atmosphere, daily oceanic and monthly hydrological signals (left), andatmospheric signals sampled at 6, 12, and 24 hours (right).

1.3 Scope of the GRACE AOD1B Product

AOD1B is intended to provide a model-based data-set that describes the time variations of the gravity potential at satellite altitudes that are caused by non-tidal mass variability in the atmosphere and oceans. The product contains for each 6-hourly time step four different sets of Stokes coefficients: 'atm' describes the global contribution of the vertically distributed atmospheric masses by explicitly taking into account the actual density distribution in the atmosphere. 'ocn' contains the contribution of the oceanic water column to ocean bottom pressure variations, 'glo' the summed effect of atmosphere represented by 'atm' and ocean represented by 'ocn'. Finally, 'oba' represents the ocean bottom pressure simulated by the ocean model in response to surface pressure and other meteorologic quantities from the lower boundary of the atmosphere. 'oba' thereby ignores any effects of the vertical distribution of the masses in the atmosphere.

1.4 History of Available AOD1B Releases

All releases of AOD1B published up to now are based on 6-hourly operational atmospheric analysis data from ECMWF, in combination with 6-hourly bottom pressure fields from different global ocean model simulations. To evaluate mass anomalies, a corresponding long-term average is calculated over all 6-hourly oceanic and atmospheric mass fields of a given time-span prior to the transformation into Stokes Coefficients.

The differences between the different releases so far available are shortly summarized in the following. Further details are provided in Chapter 4.

R**elease 01** of AOD1B is available for the period July 2000 until June 2007 and incorporates ocean bottom pressure simulated with the barotropic ocean model PPHA (Hirose et al. 2000). Atmospheric and oceanic mean fields calculated for the year 2001 are removed from all the data-sets for this release.

Release 02consists of a short test series from operational ECMWF analysis data and ocean bottom pressure of an improved version of PPHA. This dataset is not publicly available.

Release 03 is based on a first test simulation with an OMCT configuration discretized on a 1.875° latitude-longitude grid (Thomas and Dobslaw, 2005). The series is available from January 2002 until January 2007, mean fields calculated over the years 2001 and 2002 are subtracted.

A further long-term simulation with OMCT discretized on a 1.875° grid with slightly adjusted parameterizations is the basis for **release 04** (Dobslaw and Thomas, 2007). OMCT has been forced with ERA40 atmospheric reanalysis data for the time-period January 1976 to December 2000, followed by simulations forced with operational ECMWF analyses until April 2012, making it suitable for the consistent re-processing of historical satellite laser ranging observations (Flechtner et al., 2008). The mean fields removed are once more calculated for the years 2001 and 2002.

The most recent **release 05** that is described in detail in this document was introduced in early 2012. The series is based on OMCT discretized on a 1.0° latitude-longitude grid (Dobslaw et al., 2013), that has been integrated with ERA Interim reanalysis data (Dee et al., 2011) for the time-period January 1989 to December 2000, followed by simulations forced with operational ECMWF analyses. The atmospheric contribution was not changed w.r.t. release 04. Corresponding mean fields calculated for the years 2001 and 2002 are once more subtracted.

1.5 Latest Status Information on AOD1B RL05

The most recent release 05 of AOD1B is available since Jan 1st, 2001, and is currently updated on an approximately weekly basis. Up-to-date information on the status of this product can be obtained from the web-pages at www.gfz-potsdam.de/AOD1B.

AOD1B RL05 and in particular its oceanic component has been extensively tested against a number of independent data-sets, demonstrating the superiority of the latest product version with respect to previous releases. The results are summarized in the following paper:

Dobslaw, H., Flechtner, F., Bergmann-Wolf, I., Dahle, Ch., Dill, R., Esselborn, S., Sasgen, I., Thomas, M. (2013), Simulating High-Frequency Atmosphere-Ocean Mass Variability for De-Aliasing of Satellite Gravity Observations: AOD1B RL05, J. Geophys. Res., 118(C5), 10.1002/jgrc.20271.

1.6 Known Limitations of AOD1B RL05

AOD1B is intended to serve as a background model for the removal of high-frequency non-tidal variability. It entirely relies on numerical data from ECMWF and the (unconstrained) ocean model OMCT. It therefore includes a number of limitations, which are summarized in the following. An updated list of known limitations is found on the web-pages at **www.gfz-potsdam.de/AOD1B**.

OMCT simulations are intended to simulate in particular short-term variability of ocean bottom pressure in response to rapidly varying atmospheric conditions. In the long run, however, the model state is drifting more rapidly than, e.g., current state-of-the-art coupled atmosphere-ocean models that are prepared to reproduce climate variability over many centuries. Low frequency variability and **trends in OMCT** ocean bottom pressure are primarily related to ongoing warming and cooling of water masses at intermediate depths, and its secondary effects on the thermohaline circulation. They are therefore much less reliable than the high-frequency variability and should not be interpreted geophysically.

The basis of the atmospheric part of the AOD products are operational analyses from ECMWF - that is, data from a numerical weather prediction model which is intended to provide best possible state estimates and corresponding medium-range forecasts to its users. Therefore, the ECMWF is upgraded periodically to incorporate improvements in the physical model, the numerics, the data assimilation scheme, and to accommodate new observing technologies. Those changes to the model consequently lead to inconsistencies in the time-series of model states (e.g. jumps), most easily realized from series of atmospheric surface pressure at high altitudes in mountainous regions. **ECMWF model changes** are usually performed about twice a year, and are announced at the ECMWF web-pages.

1.7 AOD1B as an Operational Product of the IERS

By acknowledging the value of the AOD1B series for geodetic applications that go beyond its primary purpose of serving as a time-variable background model for GRACE gravity processing, AOD1B has been formally assigned the status of an 'operational product' of the Global Geophysical Fluid Center, a data service operated within the International Earth Rotation and Reference System Service (IERS) of the International Association for Geodesy (IAG).

2. Input Data and Models

For the calculation of the GRACE AOD1B product, different atmospheric fields and an ocean model are required. In the following chapters the input data and the ocean model are described.

2.1 Atmospheric Data

For the de-aliasing analysis GFZ regularly extracts operational analysis data at the European Center for Medium-range Weather Forecast (ECMWF) Integrated Forecast System (IFS) at synoptic times 0:00, 6:00, 12:00 and 18:00. Details on the used models can be found at http://www.ecmwf.int/research/ifsdocs/index.html. The spatial resolution is defined on a Gaussian N160 grid which corresponds to about 0.5° latitude/longitude grid resolution. Temperature and specific humidity profiles are represented at 60 (from 2001 till 1 February 2006), 91 (1 February 2006 till 25 June 2013) and since then at 137 vertical levels. The necessary fields to perform the vertical integration of the atmosphere are (see below)

- Surface Pressure (PSFC)
- Multi-level Temperature (TEMP)
- Multi-level Specific Humidity (SHUM)
- Geopotential Heights at Surface (PHISFC)

and are long-term archived at GFZ´s Information System and Data Center (ISDC) for the time span starting on July 1, 2001 until today.

To run the ocean model OMCT, the following ECMWF IFS data are acquired:

- Wind Speed at 10m height in U and V direction (U10, V10)
- Temperature at 2m level (TEMP2M)
- Surface Pressure (PSFC)
- Freshwater fluxes deduced from precipitation minus evaporation (taken from operational forecasts) (PmE)
- Sea Surface Temperature (SST) (*)
- Specific Humidity (SHUM) (*)
- Temperature at 10m level (TEMP10M) (*)
- Charnock parameters (CHAR) (*)

(*): Necessary for the transformation to wind stress components τ_x, τ_y

2.2 Ocean Model OMCT

The Ocean Model for Circulation and Tides (OMCT) is a further development of the Hamburg Ocean Primitive Equation (HOPE) model. Prognostic variables are the three-dimensional horizontal velocity fields, the sea-surface elevation, and potential temperature and salinity. The originally climatological HOPE model has been adjusted to the weather timescale and coupled with an ephemeral tidal model. Implemented is a prognostic thermodynamic sea-ice model that predicts ice-thickness, compactness, and drift. In contrast to HOPE, OMCT is discretised on a Arakawa-C-grid and allows for the calculation of ephemeral tides and the thermohaline, wind-, and pressure driven circulation as well as secondary effects arising from loading and self-attraction of the water column and nonlinear interactions between circulation and tidal induced ocean dynamics. Since tidal induced oceanic mass redistribution and corresponding gravity effects are removed from GRACE measurements by means of another algorithm, in the OMCT version applied here tidal dynamics are not taken into account.

Details concerning the applied model equations, numerical implementations, and parameterizations can be found in Wolff et al. (1996), Drijfhout et al. (1996), and Thomas (2002). A detailed discussion of the OMCT configuration used for AOD1B RL04 is given by Dobslaw (2007). In the following, only the model components of OMCT not included in HOPE and relevant for short-period mass redistributions are described.

Model equations and numerical implementations

The numerical model OMCT is based on nonlinear balance equations for momentum, the continuity equation for an incompressible fluid, and conservation equations for heat and salt. The hydrostatic and Boussinesq approximations are applied. Three-dimensional horizontal velocities, water elevation, potential temperature as well as salinity fields are calculated prognostically; vertical velocities are determined diagnostically from the incompressibility condition. Implemented is a sea-ice model with viscous-plastic rheology (Hibler, 1979) allowing a prognostic calculation of sea-ice thickness, compactness, and drift. The temporal resolution of the originally climatological model (Drijfhout et al., 1996; Wolff et al., 1996) is 20 minutes. Twenty layers exist in the vertical, the horizontal resolution is 1.0° in longitude and latitude on a Arakawa-C-grid (Arakawa and Lamb, 1977) covering the global ocean including the Arctic (77°S to 90°N). The bathymetry discretized on the 1° grid is derived from ETOPO5 and accounts for the realistic representation of important stream barriers. Depths shallower than the uppermost layer thickness are set to 20m.

Spinup. Initially, OMCT was spun up for 265 years with cyclic boundary conditions, that is, climatological wind stresses (Hellermann and Rosenstein, 1983) as well as annual mean surface temperatures and salinities (Levitus, 1982). The resulting mean circulation and internal variability is discussed in Drijfhout et al. (1996). Starting from this climatological quasi steady-state circulation, a real-time simulation was performed for the period 1989-2000 driven by 6-hourly wind stresses, 2m-temperatures, freshwater fluxes, and sea level pressure from ECMWF´s latest re-analysis ERA Interim. The resulting model state is used as initial model state for the operational OMCT simulations driven with ECMWF´s analysis and forecast fields.

Wind stress. To reproduce the wind-driven component of the general circulation the model requires wind stress at the ocean´s surface as forcing data. Since wind stress components are not provided by ECMWF´s operational analyses, wind velocities 10m above the surface need to be converted to wind stresses via

$$\tau = \rho C_D |U| U,$$

where τ is the wind stress vector at the ocean´s surface, ρ the density of air, U the horizontal wind vector 10m above the ocean´s surface, and C_D a transfer coefficient for momentum (drag coefficient) depending on U itself as well as on the stability of the boundary layer above the ocean. The algo rithm is, in principle, an inversion of the transformation from wind stresses to wind velocities done within operational ECMWF analyses and was provided by A.C.M. Beljaars from ECMWF (Beljaars, 1997).

Steric correction, freshwater fluxes, mass conservation. Baroclinic ocean general circulation models (OGCM) using the Boussinesq approximation conserve rather volume than mass and, thus, artificial mass changes are introduced. Since the artificial mass variations would cause corresponding artificial changes of ocean bottom pressure, following Greatbatch (1994) steric anomalies are accounted for by adding/subtracting a spatially uniform layer, $\delta\zeta_\rho$, to the sea-surface (see, e.g., Ponte and Stammer, 2000; Gross et al., 2003)

$$\delta\zeta_\rho = -\frac{1}{O}\int_V \frac{\delta\rho}{\rho_0} dV ,$$

where$\delta\rho$ is the instantaneous density anomaly, ρ_0 a reference density, and O, V the ocean´s surface and volume, respectively. In the OMCT run used for AOD1B RL05, the total ocean mass is kept constant at any time-step.

Oceanic bottom pressure. The output of the three-dimensional finite-difference code is ocean bottom pressure in Pa, and accounts for the effects of the thermohaline, wind- and pressure driven baroclinic circulation. Since pressure forcing is included, no assumption with respect to the response of the ocean´s surface to atmospheric pressure is required. With the hydrostatic equation the ocean bottom pressure, p_B, as a function of latitude and longitude can be written as (cf., Wünsch et al., 2001)

$$p_B = p_A + g\int_{-H}^{\zeta} \rho\, dz \approx p_A + g\rho_0\zeta + g\int_{-H}^{0} \rho\, dz ,$$

where p_A is the atmospheric pressure at sea level, g=9.80665m^2/s the mean gravitational acceleration, H the time-invariant water depth, ζ the sea surface elevation, ρ the time-space dependent sea water density, and ρ_0=1030kg/m^3 a mean reference density. The impact of individual components of the baroclinic oceanic circulation on oceanic bottom pressure and, thus, on the Earth´s time-variable gravity field is analysed in Thomas and Dobslaw (2005).

Time-mean. From atmospheric fields and OMCT output, a mean field for the period 2001-2002 has been calculated and removed. As for the barotropic case, the baroclinic sea level, ζ, the density, ρ, and consequently the bottom pressure, p_B, are defined as departures from rest; thus, these fields contain a time-mean baroclinic circulation.

Input data

Time invariant:
- bathymetry file;

Time varying:
- gridded wind velocities in 10m height;
- gridded atmospheric temperature fields 2m above surface;
- gridded freshwater fluxes deduced from precipitation minus evaporation as taken from ECMWF´s operational short range forecasts;
- gridded atmospheric pressure at sea level.

Output:

The model output required for AOD1B processing includes the following files:
- oceanic bottom pressure (contribution of the water column alone);
- atmospheric pressure at sea level (interpolated to OMCT grid);
- final model state and restart information for the next run.

Overview of basic model parameters

basic equations	nonlinear balance equation for momentum (Navier-Stokes), continuity equation, conservation equations for heat and salt
Coverage	global, 77°S – 90°N
Topography	1.0° average of ETOPO5; minimal water depth: 20m
spatial resolution	1.0° x 1.0°; 20 levels
temporal resolution	20 minutes
Forcing	wind stress/velocity, heat flux/2m-temp., atmospheric pressure from ECMWF analyses, freshwater fluxes (precipitation minus evaporation) from ECMWF forecasts
mass conservation	Enforced
Function	simulation of short-term oceanic mass redistributions due to thermohaline, wind- and pressure driven circulation under consideration of sea ice

3. Processing Strategy for the Ocean and Atmosphere

In this chapter the processing strategy for the ocean and the atmosphere is described and the corresponding mean fields, necessary for the calculation of residual pressure values, are defined. Finally, the combination of the ocean and the atmosphere is explained, which has been generally not altered during the transition from RL04 to RL05.
Note: the equations for the atmosphere have been modified w.r.t. RL04 to describe the latitude dependency of gravity. This latitude dependency was already implemented in RL04, but not sufficiently described in version 3.1 of this document!

3.1 Processing Strategy OMCT

The following figure describes the processing strategy to run the baroclinic ocean model OMCT to generate ocean bottom pressure.

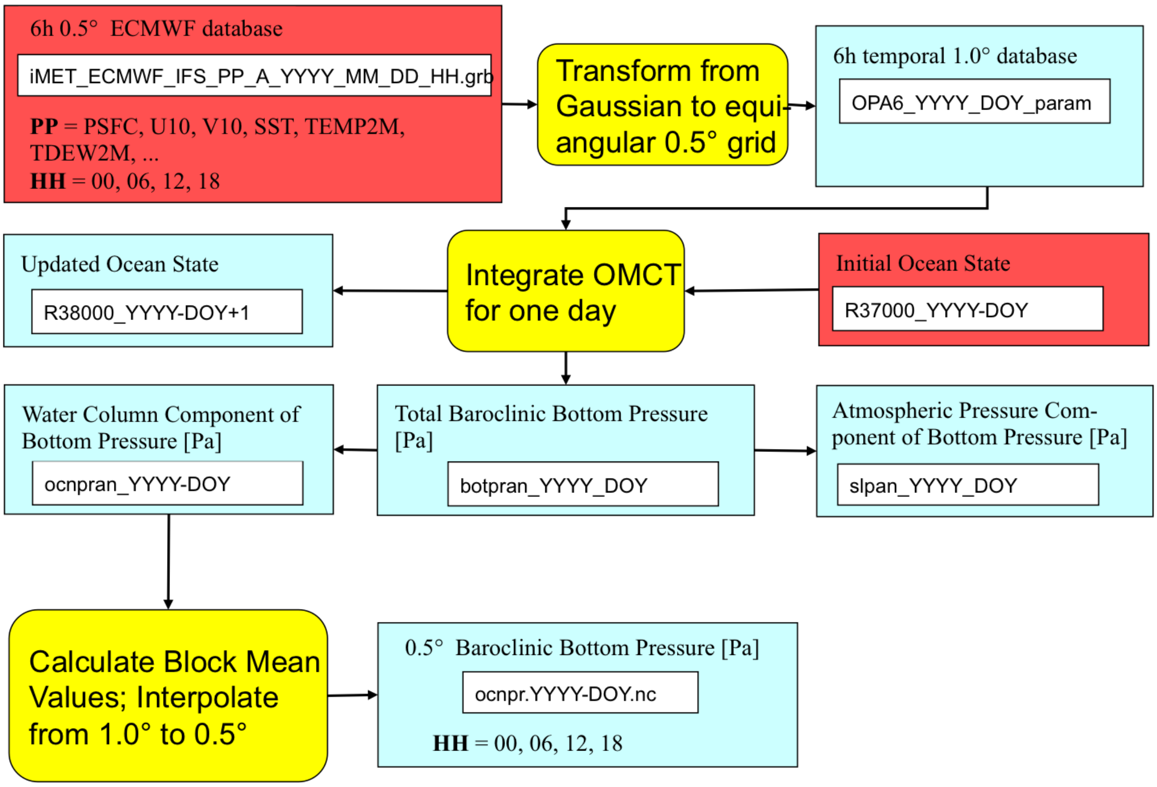

Figure 4-1: Processing Strategy Ocean using OMCT (red: input, yellow: processing step, light blue: output).

- Input data are the following 6 hourly ECMWF atmospheric fields (see chapter 2.1)
  - IMET_ECMWF_IFS_PSFC_A_YYYY_MM_DD_HH.grb: surface pressure
  - IMET_ECMWF_IFS_U10_A_YYYY_MM_DD_HH.grb: U wind speed
  - IMET_ECMWF_IFS_V10_A_YYYY_MM_DD_HH.grb: V wind speed
  - IMET_ECMWF_IFS_SST_A_YYYY_MM_DD_HH.grb: sea surface temperature
  - IMET_ECMWF_IFS_TEMP2M_A_YYYY_MM_DD_HH.grb: temperature at 2 m level
  - IMET_ECMWF_IFS_TEMP10M_A_YYYY_MM_DD_HH.grb: temperature at 10 m level
  - IMET_ECMWF_IFS_SHUM_A_YYYY_MM_DD_HH.grb: specific humidity

- IMET_ECMWF_IFS_PmE_for_A_YYYY_MM_DD_HH.grb: freshwater fluxes deduced from precipitation minus evaporation according to ECMWF short term forecasts and an initial model state of the baroclinic oceanic circulation.
- IMET_ECMWF_IFS_CHAR_A_YYYY_MM_DD_HH.grb: Charnock parameters

- The ECMWF data are transformed from a N160 gaussian to a 1.0° equidistant grid. This temporal ECMWF data base linearly interpolated to the OMCT time step of 20 minutes and the initial ocean model state force the OMCT. As a result the ocean bottom pressure fields of the epochs at 0, 6, 12, 18 hours are produced by OMCT. Additionally, restart information to initiate the next OMCT run is stored.
- For the later combination with the atmosphere the output grids are interpolated to 0.5° block mean values.
- The baroclinic ocean bottom pressure fields for the period 2001-2002 have been used to calculate a mean ocean bottom pressure field which is used to derive residual bottom pressure fields for individual time-steps.

3.2 Processing Strategy Atmosphere

To take into account the atmospheric mass variations for the calculation of the de-aliasing product two different methods have been coded: The surface pressure (SP) and the vertical integration (VI) approach. In the following only the VI approach, which is used for AOD1B RL05, is described. For the SP approach we refer to the Revision 3.1 document.

Note: For the VI approach also a gravity acceleration has to be used. In the RL05 (and also in the RL04 case, even if not explicitly noted in the Release 3.1 version of this document), a latitude weighted value is derived from the normal WGS84 gravity at the equator and the pole. Consequently, the following equations are slightly different than provided in the version 3.1 of this document. But, the software and the ‘atm’ coefficients used to calculate VI is exactly the same in version 3.1 and 4.0.

Fundamental Formulae

If the vertical structure of the atmosphere shall be taken into consideration (as for RL05) the vertical integration of the atmospheric masses has to be performed. For this case we start with some general basic formulas. Surface pressure data can be easily transformed into gravity harmonics by spherical harmonic analysis with integration and by applying specific factors for re-scaling the spherical harmonic coefficients. The gravitational potential V at a point outside the Earth due to heterogeneous mass distribution inside the Earth is expressed by a spherical harmonic expansion using normalized coefficients C_{nm} and S_{nm} of degree n and order m (Heiskanen and Moritz, 1967, 2-34, 2-35 with 2-40).

$$V = \frac{kM}{r}\sum_{n=0}^{\infty}\sum_{m=0}^{n}\left(\frac{a}{r}\right)^n P_{nm}(\cos\theta)(C_{nm}\cos m\lambda + S_{nm}\sin m\lambda) \tag{3-1}$$

$$C_{nm} = \frac{1}{(2n+1)Ma^n}\iiint_{Earth} r^n P_{nm}(\cos\theta)\cos m\lambda \, dM \tag{3-2}$$

$$S_{nm} = \frac{1}{(2n+1)Ma^n}\iiint_{Earth} r^n P_{nm}(\cos\theta)\sin m\lambda \, dM$$

with the mass, volume or surface elements:

$$dM = \rho dV = \rho r^2 dr \sin\theta \, d\theta d\lambda = r^2 q \sin\theta \, d\theta d\lambda = r^2 q dS \tag{3-3}$$

Introduction of this into (3-1) and (3-2) and introduction of surface load and surface pressure (see AOD1B Product Description Document for Releases 01 to 04) results finally in

$$\begin{aligned} C_{nm} &= -\frac{1}{(2n+1)Ma^n} \iint_{Earth} \left[\int_{r_s}^{r_{top}} r^{n+2} \rho dr \right] P_{nm}(\cos\theta) \cos m\lambda \sin\theta \, d\theta \, d\lambda \\ S_{nm} &= -\frac{1}{(2n+1)Ma^n} \iint_{Earth} \left[\int_{r_s}^{r_{top}} r^{n+2} \rho dr \right] P_{nm}(\cos\theta) \sin m\lambda \sin\theta \, d\theta \, d\lambda \end{aligned} \tag{3-4}$$

Using the hydrostatic equation:

$$\rho \, dr = -\frac{dP}{g(\theta, r)} \tag{3-5}$$

we get:

$$\begin{aligned} C_{nm} &= -\frac{1}{(2n+1)Ma^n} \iint_{Earth} \left[\int_{P_s}^{0} \frac{r^{n+2}}{g(\theta,r)} dP \right] P_{nm}(\cos\theta) \cos m\lambda \sin\theta \, d\theta \, d\lambda \\ S_{nm} &= -\frac{1}{(2n+1)Ma^n} \iint_{Earth} \left[\int_{P_s}^{0} \frac{r^{n+2}}{g(\theta,r)} dP \right] P_{nm}(\cos\theta) \sin m\lambda \sin\theta \, d\theta \, d\lambda \end{aligned} \tag{3-6}$$

The gravity acceleration in height r (g_r) can be approximated from the mean gravity acceleration g by:

$$g(\theta, r) = g(\theta) \left(\frac{a}{r}\right)^2 \tag{3-7}$$

Then we get:

$$\begin{aligned} C_{nm} &= -\frac{1}{(2n+1)Ma^{n+2}} \iint_{Earth} \left[\int_{P_s}^{0} \frac{r^{n+4}}{g(\theta)} dP \right] P_{nm}(\cos\theta) \cos m\lambda \sin\theta \, d\theta \, d\lambda \\ S_{nm} &= -\frac{1}{(2n+1)Ma^{n+2}} \iint_{Earth} \left[\int_{P_s}^{0} \frac{r^{n+4}}{g(\theta)} dP \right] P_{nm}(\cos\theta) \sin m\lambda \sin\theta \, d\theta \, d\lambda \end{aligned} \tag{3-8}$$

The radial coordinate r is composed of (see figure 3-2 and (Wahr and Svensson, 1999)):

(3-9)

$$r = r_s + \delta r = a + \xi + h + \delta r = a + \xi + z$$

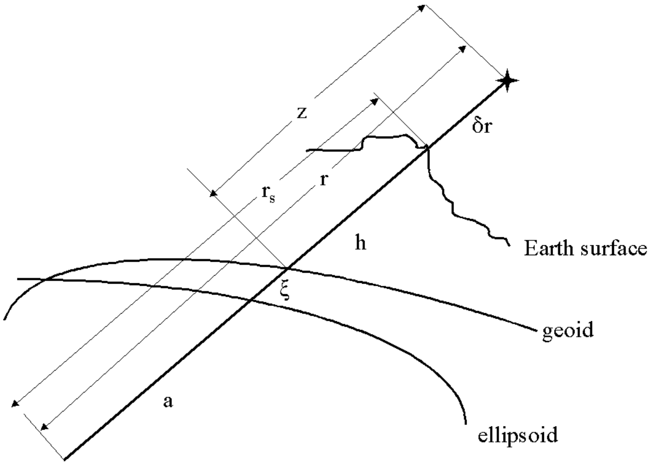

Figure 3-2: Radial component r used in vertical integration

ξ is the height of the mean geoid above the mean sphere r = a. h is the elevation of the Earth´s surface above the mean geoid (Earth´s surface topography). The geopotential height ϕ a point * above the Earth´s surface is defined by:

(3-10)

$$\phi = \frac{1}{g_0}\int_0^z g(\theta, r)\, dz = \frac{g(\theta)}{g_0}\left(\frac{z}{a+z}\right)a$$

After transformation we get:

(3-11)

$$\phi = \frac{g(\theta)}{g_0}\left(\frac{z}{a+z}\right)a \Rightarrow \frac{\phi}{a} = \frac{g(\theta)}{g_0}\left(\frac{z}{a+z}\right) \Rightarrow z = \left(\frac{a+z}{a}\right)\phi\frac{g_0}{g(\theta)} \Rightarrow z = \left(\frac{\phi a}{a} + \frac{\phi z}{a}\right)\frac{g_0}{g(\theta)} \Rightarrow$$
$$\phi = \frac{g(\theta)}{g_0}z - \frac{\phi z}{a} \Rightarrow \phi = z\left(\frac{g(\theta)}{g_0} - \frac{\phi}{a}\right) \Rightarrow z = \frac{\phi}{\left(\frac{g(\theta)}{g_0} - \frac{\phi}{a}\right)}$$

Then it follows:

(3-12)

$$r = a + \frac{\phi}{\left(\frac{g(\theta)}{g_0} - \frac{\phi}{a}\right)} + \xi = \frac{a}{\left(1 - \frac{g_0}{g(\theta)}\frac{\phi}{a}\right)} + \xi$$

This expression is substituted in (3-13):

(3-13)

$$C_{nm} = -\frac{1}{(2n+1)Ma^{n+2}} \iint\limits_{Earth} \left[\int\limits_{P_s}^{0} \frac{1}{g(\theta)} \left(\frac{a}{1 - \frac{g_0}{g(\theta)} \frac{\phi}{a}} + \xi \right)^{n+4} dP \right] P_{nm}(\cos\theta) \cos m\lambda \sin\theta \, d\theta \, d\lambda$$

$$S_{nm} = -\frac{1}{(2n+1)Ma^{n+2}} \iint\limits_{Earth} \left[\int\limits_{P_s}^{0} \frac{1}{g(\theta)} \left(\frac{a}{1 - \frac{g_0}{g(\theta)} \frac{\phi}{a}} + \xi \right)^{n+4} dP \right] P_{nm}(\cos\theta) \sin m\lambda \sin\theta \, d\theta \, d\lambda$$

After including the degree dependent term into the integral (for numerical reasons) and introducing again the elastic deformation of the solid Earth we get the following final formulas for determination of the gravity coefficients using the vertical integration approach:

(3-14)

$$C_{nm} = -\frac{a^2(1+k_n)}{(2n+1)M} \iint\limits_{Earth} \frac{1}{g(\theta)} \left[\int\limits_{P_s}^{0} \left(\frac{a}{a - \frac{g_0}{g(\theta)} \phi} + \frac{\xi}{a} \right)^{n+4} dP \right] P_{nm}(\cos\theta) \cos m\lambda \sin\theta \, d\theta \, d\lambda$$

$$S_{nm} = -\frac{a^2(a+k_n)}{(2n+1)M} \iint\limits_{Earth} \frac{1}{g(\theta)} \left[\int\limits_{P_s}^{0} \left(\frac{a}{a - \frac{g_0}{g(\theta)} \phi} + \frac{\xi}{a} \right)^{n+4} dP \right] P_{nm}(\cos\theta) \sin m\lambda \sin\theta \, d\theta \, d\lambda$$

From the meteorological analysis centers usually not the geopotential height Φ, but temperature and specific humidity are available on the model or full levels and are considered constant within the layers. Therefore, before the integration with formula (3-14) can be performed numerically, the geopotential heights for all levels have to be computed. This computation can be done in the following way (White, 2001, formula 2.21; Schrodin 2000, page 51) (N_{Level} represents the lowest level).

(3-15)

$$\phi_{k+1/2} = \phi_s + \frac{1}{g_0} \sum_{j=k+1}^{N_{level}} R_{dry_j} T_{v_j} \ln \frac{P_{j+1/2}}{P_{j-1/2}}$$

with
- $\Phi_{k+1/2}$ Geopotential height at half level (layer interfaces)
- Φ_S Geopotential height at surface (if provided as potential divide by g_0)
- R_{dry} Gas constant for dry air = 287 $m^2/(s^2K)$ = 287 J/(kgK)
- T_v Virtual temperature
- $P_{k+1/2}$ Pressure at half level (layer interface)

$$T_v = (1 + 0.608H)T \qquad (3\text{-}16)$$

- H specific Humidity
- T Temperature

$$P_{k+1/2} = a_{k+1/2} + b_{k+1/2} P_s \tag{3-17}$$

$a_{k+1/2}$ Model dependent coefficient
$b_{k+1/2}$ Model dependent coefficient
Both coefficients are provided in ECMWF GRIB files, for DWD see Schroding 2000, p.51)

The geopotential heights at pressure levels finally can be used to compute the inner integral in (3-14). In the second term ξ/a, the mean geoid above the sphere r=a can be approximated by the geopotential height at the Earth´s surface which is available at ECMWF.

Processing Sequence

Starting points are point values of surface pressure and geopotential height grids on the Earth's surface (surface is defined as a half level)and point values of temperature and specific humidity at all model levels (full levels) of the atmospheric model in the same global grid. All these equiangular point grids are transformed to block mean grids by applying a mean value operator to the 4 corner points. Then the pressure at all model half levels (formula 3-17) is computed by using the atmospheric model specific interpolation coefficients (a, b). These pressure values, the virtual temperature, which is computed from the real temperature and the specific humidity in each model full level (3-16) and the surface geopotential heights are used to compute the geopotential heights for all half levels. For this also a gravity acceleration has to be used. In the RL05 (and also in the RL04 case, even if not explicitly noted in the Release 3.1 version of this document), a latitude weighted value is derived from the normal WGS84 gravity at the equator and the pole. Then the integration is done numerically for each degree separately using the geopotential heights of the model levels. These intermediate results are stored in a three dimensional array with longitude, latitude and degree as indices. Finally the spherical harmonic analysis is performed for each degree of the spherical harmonic series separately, in order to take into account the degree dependent exponent in equation (3-14). Finally the complete spherical harmonic series is written on a binary spherical harmonic series file which is input to derive the final ASCII AOD1B product.

To analyze gravity variations caused by atmospheric vertical integrated pressure variations a corresponding mean field covering at least one year of data has to be subtracted (in order to eliminate seasonal effects in the mean field) from the inner integral of above equation 3-14 (see also chapter 3.3). After subtraction of the mean pressure field residual pressure data, which represent mass variations with respect to the mean field are available:

$$C_{nm} = -\frac{a^2(1+k_n)}{(2n+1)M} \iint_{Earth} \frac{1}{g(\theta)} \left(\left[\int_{P_s}^{0} \left(\frac{a}{a - \frac{g_0}{g(\theta)}\phi} + \frac{\xi}{a} \right)^{n+4} dP \right] - \bar{P}_{VI} \right) P_{nm}(\cos\theta) \cos m\lambda \sin\theta \, d\theta \, d\lambda \tag{3-18}$$

$$S_{nm} = -\frac{a^2(1+k_n)}{(2n+1)M} \iint_{Earth} \frac{1}{g(\theta)} \left(\left[\int_{P_s}^{0} \left(\frac{a}{a - \frac{g_0}{g(\theta)}\phi} + \frac{\xi}{a} \right)^{n+4} dP \right] - \bar{P}_{VI} \right) P_{nm}(\cos\theta) \sin m\lambda \sin\theta \, d\theta \, d\lambda$$

For a better clarification of this processing sequence a pseudo code is provided below.

Read global surface pressure from GRIB file
    IMET_ECMWF_IFS_PSFC_A_YYYY_MM_DD_HH.grb
Read global surface geopotent. height from GRIB file
    IMET_ECMWF_IFS_PHISFC_A_YYYY_MM_DD_HH.grb
Read global model level temperatures from GRIB file

IMET_ECMWF_IFS_TEMP_A_YYYY_MM_DD_HH.grb
Read global model level specific humidity from GRIB file
IMET_ECMWF_IFS_SHUM_A_YYYY_MM_DD_HH.grb
Compute for all global data sets block mean values
Do for all block means in the global grid files
Do for all model levels
Compute pressure at model level (3-17)
Compute virtual temperature a model level (3-16)
Compute geopotential height of model level by summing up individual heights and add surface geopotential height (3-15)
Compute expression in large brackets of inner integral in (3-14)
Do for all degrees of spherical harmonic series
Apply exponent and do numerical integration by multiplication with pressure difference of model levels and summation of all model levels
Store result in temporary 3-D field with long., latitude and degree as indices
End Do
End Do
End Do
Do for all degrees of spherical harmonic series
Subtract mean contribution for this degree by reading it from a separate file
Perform spherical harmonic analysis for this degree using the temporary 3-D field (3-14)
Store coefficients of this degree in result vector
End Do
Write spherical harmonic series to output file

3.3 Mean Ocean and Atmospheric Pressure Fields

To calculate mass anomalies that represent the deviation from a certain reference state, a long-term average is calculated for each component, i.e., the 3D atmospheric mass distribution, as well as the oceanic and atmospheric contributions to ocean bottom pressure. For RL05, those mean fields are calculated for the time period 2001+2002.

3.4 Coefficients available in AOD1B: atm, ocn, glo, oba

The different coefficient sets contained in AOD1B that represent the individual and combined effect of atmosphere and ocean are calculated in the following way:

'atm': difference between vertically integrated density of the atmosphere and the corresponding mean field

'ocn': difference between the water column contribution to ocean bottom pressure and the corresponding mean field

'glo': sum of 'atm' and 'ocn' mass anomalies

'oba': sum of the water column contribution to the ocean bottom pressure anomalies (i.e., the 'ocn' data-set) and the atmospheric contribution to ocean bottom pressure anomalies (i.e., the difference between the atmospheric contribution to ocean bottom pressure and the corresponding mean field). In contrast to 'glo', this data-set is set to zero at the continents.

All four sets of mass anomalies are subsequently transformed into Stokes coefficients. Please note that although they are provided within the AOD1B products, the degree 0 and 1 terms shall not be used during determination of GRACE products.

3.5 Consideration of Atmospheric Tides

Atmospheric tides that are primarily excited in the middle atmosphere are most prominent at frequencies of one (i.e., S1) and two (i.e., S2) cycles per solar day. Periodic changes are also present in surface pressure and wind fields, thereby causing an additional oceanic response to atmospheric tides (Dobslaw and Thomas, 2005a).

Signals from atmospheric tides are fully retained in the vertically integrated atmospheric part of AOD1B. However, S2 corresponds to the Nyquist frequency for 6-hourly resolved data-sets, implying that only a fraction of the signal at this period can be reconstructed.

Therefore, the recommendation for GRACE Precise Orbit Determination (POD) and avoidance of double bookkeeping using the atmospheric part of AOD1B is as follows:

- Reduce S2 at 0h, 6h, 12h and 18h from AOD1B using the atmospheric tide model applied in POD
- Apply the atmospheric tide model for each integration step size during POD

In the oceanic part of AOD1B, S1 signals are retained as well. However, variability at the S2 frequency is not included in the oceanic contribution to ocean bottom pressure: Since S2 is among the largest ocean tides, it is separately accounted for by means of a separate ocean tide model. Those models are typically constrained by satellite altimetry or other sea-level observations that do not distinguish between gravitationally induced tides and pressure induced tides as long as they are acting at the same frequency. It is therefore assumed that the oceanic response to atmospheric tides at the S2 frequency is contained in the tide model: it is therefore not appropriate to introduce it into POD for a second time via AOD1B.

Consequently, the atmospheric contribution to ocean bottom pressure as simulated by OMCT does not include signals at S2. The difference between 'glo' and 'oba' over the oceans therefore represents the difference between both the vertically distributed atmospheric masses and surface pressure, and the effect of the semidiurnal atmospheric tide S2.

3.6 Time-Averaged AOD1B Products: GAA, GAB, GAC, and GAD

In order to allow users to re-introduce time-mean signal parts that have been removed during the gravity field processing by applying AOD1B, monthly mean gravity fields prepared by the SDS Centers are routinely accompanied by time-averaged AOD1B products. Those products are always averaged over whole days, regardless of whether full or partial day's data were used in creating the particular GRACE monthly gravity field.

'GAA': monthly average of 'atm' coefficients

'GAB': monthly average of 'ocn' coefficients

'GAC': monthly average of 'glo' coefficients

'GAD': monthly average of 'oba' coefficients

Please note that - as with the daily AOD1B products - the GAA to GAD products include degree 0 and 1 terms. Users shall be aware not to apply these coefficients in their calculations.

3.7 Discontinuities in atmospheric pressure data and associated correction products GAE and GAF

The basis of the atmospheric part of the AOD1B products are Operational analyses from ECMWF - that is, data from a numerical weather prediction model which is intended to provide best possible state estimates and corresponding medium-range forecasts to its users. Therefore, the ECMWF is upgraded periodically to incorporate improvements in the physical model, the numerics, the data assimilation scheme, and to accommodate new observing technologies. Those changes to the model consequently may lead to inconsistencies in the time-series of model states, most easily realized from series of atmospheric surface pressure at high altitudes in mountainous regions.

These in-homogeneities consist in positive and negative jumps of surface pressure and surface geopotential time series at specific locations (e.g. high elevation points, Fig. 3-3). Between 2001 and 2013 these jumps occurred two times:

1- between 2006-01-29 18h and 2006-01-30 00h

2- between 2010-01-26 00h and 2010-01-26 06h

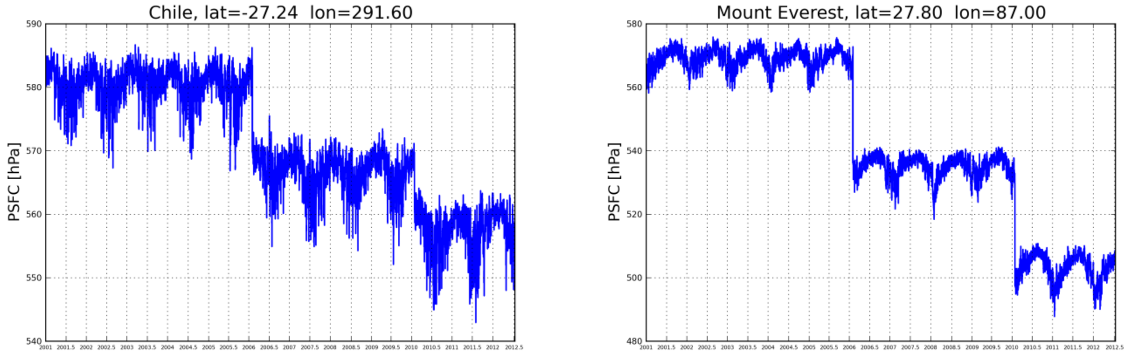

Figure 3-3: 6-hourly surface pressure variation between January 2001 and June 2012 at a location in Chile (left) and over Mount Everest (right). Two discontinuities are detected in January 2006 and January 2010.

We observed that those inconsistencies are strictly associated with upgraded horizontal and vertical resolution at ECMWF.

Jumps in the surface pressure and surface geopotential time series propagate through the vertical integration and spherical harmonics analysis affecting the resulting gravity field. Therefore, they can lead to wrong regional trend estimation of mass variations over a time span that includes one or both of these jumps.

In order to overcome this problem, a correction strategy for the de-aliasing products is needed. Since only atmospheric parameters are affected, also only 'atm' and 'glo' coefficients need to be corrected. An **accurate approach** would be to add supplementary AOD1B products to the 6-hourly AOD1B data sets 'atm' and 'glo' during GRACE Precise Orbit Determination (POD). The derived gravity solutions as well as the monthly averages 'GAA' and 'GAC' will result free from errors (jumps) present in the atmospheric input data. Unfortunately, for this purpose, all GSM-solutions would have to be reprocessed with the corrected AOD1B. This is not doable for RL05 at the moment, but is planned for a future RL06. There we plan to reprocess 6-hourly (jump) corrected AOD1B which can then be applied to derive improved RL06 gravity field solutions. Also, we will check routinely resolution changes at ECMWF. If a new jump appears, we will estimate new correction coefficients and consequently apply them at the AOD1B level without the need of additional products such as 'GAE' and 'GAF' as described below.

Till then, as an **intermediate solution**, we neglect the error introduced at orbit level and suggest correcting the atmospheric and oceanic temporal-averaged products 'GAA' and 'GAC' by using two additional products called 'GAE' and 'GAF', which correct the jumps in January 2006 and January 2010, as follows:

1- add 'GAE' (monthly average of 'atm' correction coefficients) to 'GAA' and 'GAC' between February 2006 (included) and January 2010 (included).

2- add 'GAF': monthly average of 'atm' correction coefficients to be added to 'GAA' and 'GAC' after February 2010 (included).

Users who are not interested in introducing back oceanic and atmospheric signals, have the possibility to correct gravity field solutions with reduced atmosphere and ocean (the standard ‘GSM’ products) by subtracting 'GAE' (between February 2006and January 2010) and 'GAF' (after February 2010) from 'GSM'.

The 'atm' and 'glo' coefficients to derive 'GAE' and 'GAF' are estimated by comparing the standard atmosphere coefficients with independently generated coefficients based on ECMWF ERA-Interim reanalysis. The latter is known to be more homogenous and stable in time and therefore more appropriate for long-term analysis (e.g. trend analysis).

The basic ideas and the computation of these new products is described in the following more detailed:

t1 = 2006-01-30 00h (exact occurrence of the first jump)
t2 = 2010-01-26 06h (exact occurrence of the second jump)

- We first calculate 6h differences after and before the jumps of standard 'atm' coefficients. For the first jump: 'atm' at t1 minus 'atm' at 2006-01-29 18h. For the second jump: 'atm' at t2 minus 'atm' at 2010-02-26 00h. These atmospheric gravity variations include the true 6h 'atm' differences plus an error due to the jump (Fig. 3-4).

- We calculate the same 6h differences of new 'atm' coefficients generated using atmospheric input parameters from ERA-Interim. We assume that these new atmospheric gravity variations represent the true (unbiased) 6h 'atm' differences (Fig. 3-5).Note that for the ERA-Interim products a corresponding mean field based on ERA-Interim data for the years 2001 and 2002 has to be calculated and removed.

- Calculation of correction coefficients J1 for the time between t1 and t2 result as the difference between the new and the standard atmospheric gravity variations at t1. Since J1 is constant in time, the monthly average 'GAE' is equal to J1.

- Calculation of correction coefficients J2 for the time after t2 result as the difference between the new and the standard atmospheric gravity variations at t2 plus J1. Again, monthly average 'GAF' is equal to J2.

Fig. 3-4 shows 6-hourly atmospheric gravity variations expressed in equivalent water height (EQWH) at t1 (left) and t2 (right). Besides realistic signatures of surface pressure variations one can notice spurious artifacts in form of negative (blue) and positive (red) spots. Fig. 3-5 shows the same 6-hourly gravity variations but this time with corrected 'atm'. Patterns are smoother and previous artifacts disappear in both cases.

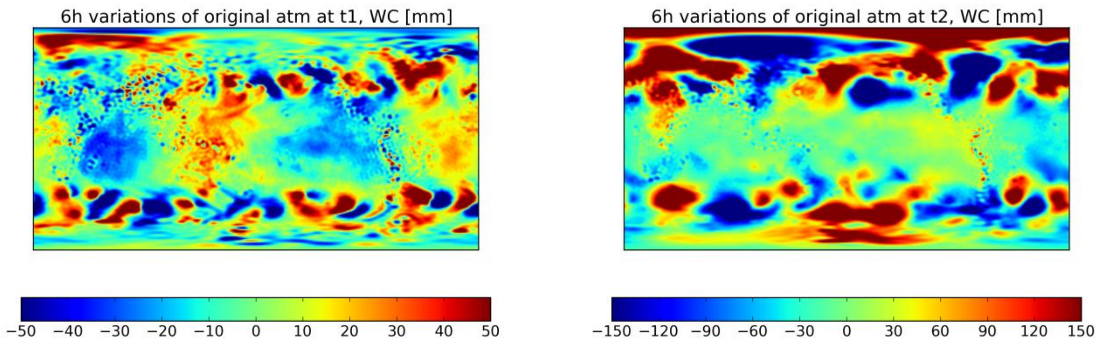

Figure 3-4: original atmospheric gravity variations at t1 (left) and t2 (right) in mm EQWH. Jumps appear as red and blue spots.

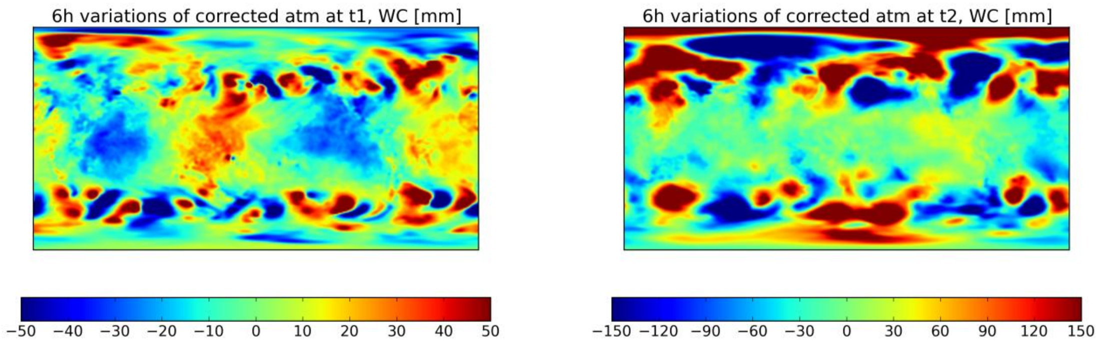

Figure 3-5: corrected atmospheric gravity variations at t1 (left) and t2 (right) in mm EQWH.

The exact locations affected by biases can be highlighted by comparing the corrected and the original coefficients (Fig. 3-6).

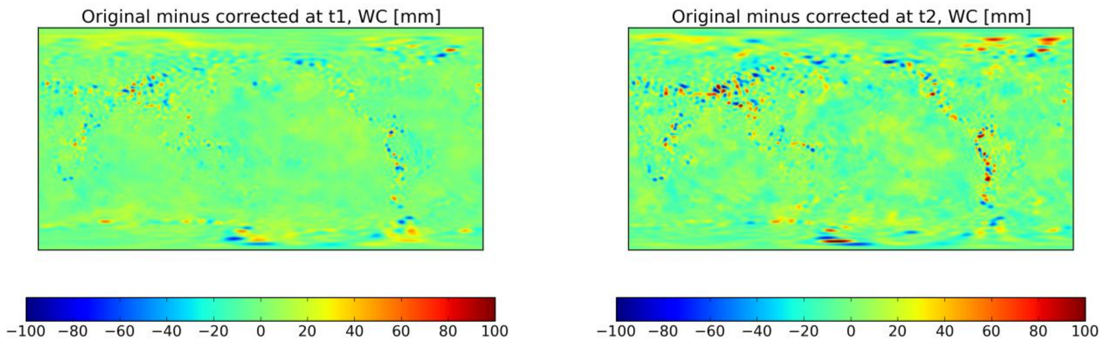

Figure 3-6: biased locations at t1 (left) and t2 (right) in mm EQWH.

If we look at the time series of original and corrected 6-hourly atmospheric gravity variations at some problematic locations, we can conclude that corrected solutions are much more stable in time and no longer affected by jumps (Fig. 3-7).

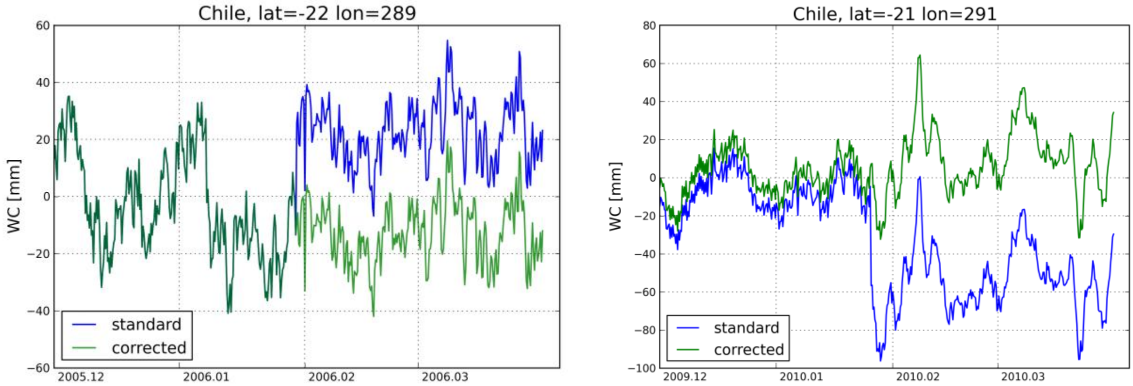

Figure 3-7: standard and corrected atmospheric gravity variations at a location in Chile for t1 (left) and t2 (right).

The global effect on gravity field is represented by the GAE and GAF products themselves. The corrected gravity fields differ from the original ones by a latitude and longitude dependent time-constant bias. Between February 2006 and January 2010 the bias is exactly GAE and after February 2010 it is GAF. GAF values present a range of 53 mm clearly greater than the 37 mm of GAE, since both jumps add up to GAF. Extreme values are present over both land and water (Fig. 3-8), suggesting that an inverse barometric (IB) reaction of the ocean should be investigated for the next RL06 (forcing of 6-hourly OMCT by corrected pressure). Some descriptive statistics are shown in Table 3-1.

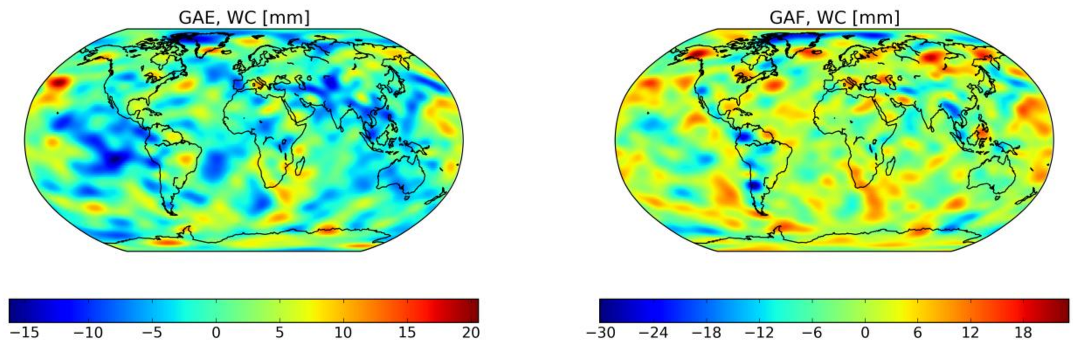

Figure 3-8: GAE and GAF correction coefficients in mm EQWH.

In order to verify if the proposed intermediate solution (a-posteriori correction of Level-2 gravity field products by GAE/GAF) is a good approximation of the accurate one (corrected AOD1B used in POD), we calculated the corresponding effect for January and February 2010 (Fig. 3-9). The global differences present considerable low mean (-0.01 mm EQWH for both months) and standard deviation (1.1 mm EQWH for January and 0.7 mm EQWH for February). We can notice a slightly worse performance in January, probably due to the fact that the jump occurs on the 26th and GAE ignores the last four days of the month. Nevertheless, we can conclude that the error, also for the minimum and maximum values, introduced by the proposed provisional solution is negligible w.r.t. the current GRACE error level (see Table 3-1).

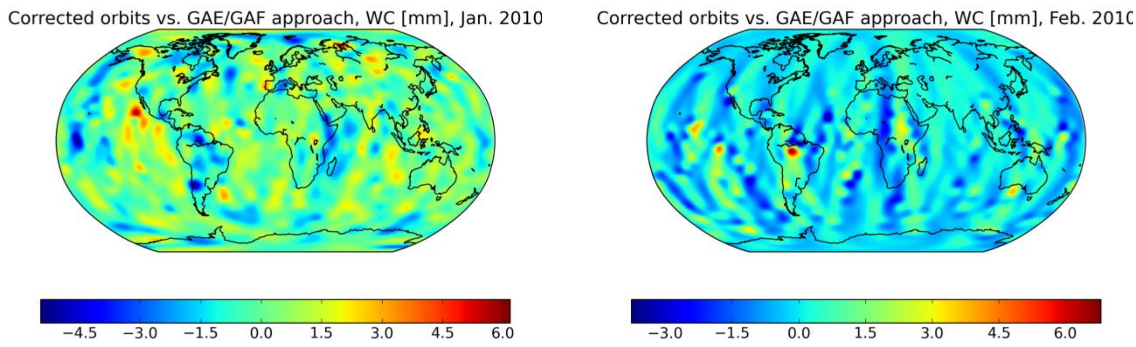

Figure 3-9: monthly gravity field difference in mm EQWH between the accurate and intermediate approach for January 2010 (left) and February 2010 (right).

	GAE [mm]	GAF [mm]	Methods Difference Jan 2010 [mm]	Methods Difference Feb 2010 [mm]
min	-16.3	-30.1	-5.5	-3.8
max	20.6	23.1	6.2	6.8
mean	4.5	6.2	-0.01	-0.01
std	-0.05	-0.7	1.1	0.7

Table 3-1: statistical information on GAE, GAF, and on the difference of the accurate and intermediate method

4. Available Releases of the AOD1B Product

The following releases of AOD1B are available at the archives. Although this document release is intended to describe RL05 only, the history of previous release might be interesting for the user. For details on RL00 till RL04 see also Release 3.1 of this document.

Release	Period	Ocean Model	Mean Field	S2 Tide Atmosphere(3)	S2 Tide Ocean
RL00	June 2000-April 2003 (1)	PPHA	2001	Included	Included
RL01	June 2000-June 2007	PPHA	2001	Included	Included
RL02	(2)	PPHA	2001+2002	Included	Removed(4)
RL03	Jan 2002-January 2007	OMCT(5)	2001+2002	Included	Removed(4)
RL04	Jan 2001-April 2012	OMCT(6)	2001+2002	Included	Removed(4)
RL05	Jan 2001-today	OMCT(7)	2001+2002	Included	Removed (4)

(1) RL00 generation stopped in April 2003 and was substituted by RL01. Both AOD products are exactly the same, except that besides the global combined mass variation also the atmospheric and oceanic contributions are provided in the RL01 AOD1B product

(2) Only available for May 2003, July 2003, August 2003, September 2003, November 2003, February 2004, December 2004 and January 2005

(3) The S2 atmospheric tide is still included in the atmospheric part of the AOD1B products. When using an atmospheric tide model in POD users might have to avoid a double book-keeping by reduction of the S2 part from the AOD1B using their atmospheric tide model prior to POD.

(4) The S2 atmospheric tide was removed from surface pressure before forcing PPHA or OMCT using a strategy described in Ponte and Ray (2002). This is done to avoid double-modeling, once in the ocean's response to pressure variations and once in the altimetric ocean tide models. Consequently, users should take care to use an ocean tide model which has the total (gravitational plus atmospheric) S2 tide in!

(5) The RL03 OMCT outputs were calculated with the condition of vanishing net freshwater fluxes during the period Jan 2002 to December 2004. Since January 2005 this condition is replaced by a condition that instantaneously conserves mass. As a consequence, gravity field products of the period January 2002 to December 2004 corrected with this version of OMCT show artificial slopes over land which has to be corrected by the corresponding GAB products (for definition see below).GRACE users which are analyzing GFZ RL03 or JPL RL02 time-series are referred to GRACE Technical Note #04 for further information.

(6) To overcome the RL03 problems, all RL04 OMCT outputs were calculated by a condition that instantaneously conserves mass. Additionally, the OMCT RL04 bathymetry was adjusted to the AOD1B software land-ocean mask (used to combine atmospheric and oceanic contributions), the thermodynamic sea ice model was updated and a new data set for surface salinity relaxation was taken into account. Besides the 6-hourly atmosphere, ocean and combined mass variations, RL04 also provides simulated OMCT ocean bottom pressure anomalies: the so-called 'oba' coefficients.

(7) The generation of RL01 and RL04 has been stopped according to above table and it was continued with the routine generation of RL05 only.

5. AOD1B and OCN1B Format and Content Description

In the following chapters the output format and the content of the atmosphere and ocean de-aliasing product (AOD1B) is described.

AOD1B products are regularly updated in the GRACE ISDC on a daily basis using the GRACE level-1 filename convention “AOD1B_YYYY-MM-DD_S_RL.EXT.gz” (Case *et al*., 2002) where “YYYY-MM-DD” is the corresponding date, the GRACE satellite identifier “S” is fixed to X (meaning product cannot be referred to GRACE-A or -B), RL is an increasing release number and EXT is fixed to asc (ASCII data). For data transfer simplification the products are gnu-zipped (suffix “gz”).

Each file consists of a header with a dedicated number of lines (NUMBER OF HEADER RECORDS) and ends with a constant header line (END OF HEADER). The first part of the header is based on the level-1 instrument product header convention (Case *et al*., 2002) and gives more general information on the product (header lines PRODUCER AGENCY to PROCESS LEVEL). These lines are accomplished by a certain number of header lines describing the de-aliasing product more precisely like

`PRESSURE TYPE (SP OR VI)`	:	Surface Pressure or Vertical Integration approach
`MAXIMUM DEGREE`	:	The maximum degree of the spherical harmonic series
`COEFFICIENT ERRORS (YES/NO)`	:	Yes, if errors are added to the coefficients
`COEFF. NORMALIZED (YES/NO)`	:	YES, if the coefficients are normalized
`CONSTANT GM [M^3/S^2]`	:	GM value used for computation
`CONSTANT A [M]`	:	semi-major axis value used for computation
`CONSTANT FLAT [-]`	:	flattening value used for computation
`CONSTANT OMEGA [RAD/S]`	:	Earth rotation rate used for computation
`NUMBER OF DATA SETS`	:	Number of data fields per product
`DATA FORMAT (N,M,C,S)`	:	Format to read the data (depending on header line

The NUMBER OF DATA SETS is 12 or 16 (RL04 and RL05) because for each 6-hours 3 or 4 (RL04 and RL05) different spherical harmonic series (incl. degree 0 and 1) up to a MAXIMUM DEGREE (defined in the header, 100 for all releases) are provided (see also comment 6 in chapter 4). Before calculation of these spherical harmonic series the 0.5º block means are defined as follows (also depending on PRESSURE TYPE (SP OR VI) defined in the header):

1. DATA SET TYPE “glo” (GLObal atmosphere and ocean combination):

Land:	[SP-SP(mean)] or [VI-VI(mean)]
Defined ocean area:	[ocean-ocean(mean) + SP-SP(mean)] or [ocean-ocean(mean) + VI-VI(mean)]
Undefined ocean area:	0

2. DATA SET TYPE “atm” (global ATMosphere):

Land area:	[SP-SP(mean)] or [VI-VI(mean)]
Defined ocean area:	[SP-SP(mean)] or [VI-VI(mean)]
Undefined ocean area:	[SP-SP(mean)] or [VI-VI(mean)]

3. DATA SET TYPE “ocn” (OCeaN area):

Land:	0
Defined ocean:	ocean-ocean(mean)
Undefined ocean:	0

4. DATA SET TYPE “oba” (Ocean Bottom pressure Analysis, only RL04 and RL05):

Land:	0	
Defined ocean:	[ocean-ocean(mean) + SP-SP(mean)]	(see Note 2 below!)
Undefined ocean:	0	

The following is an example for the AOD1B_2002-05-01_X_05.asc RL05product, where for simplification only the two first and last coefficients of each data set are given:

```
PRODUCER AGENCY                 : GFZ
PRODUCER INSTITUTION            : GFZ
FILE TYPE ipAOD1BF              : 999
FILE FORMAT 0=BINARY 1=ASCII    : 1
NUMBER OF HEADER RECORDS        : 29
SOFTWARE VERSION                : atm_ocean_dealise.05
SOFTWARE LINK TIME              : Not Applicable
REFERENCE DOCUMENTATION         : GRACE De-aliasing ADD
SATELLITE NAME                  : GRACE X
SENSOR NAME                     : Not Applicable
TIME EPOCH (GPS TIME)           : 2000-01-01 12:00:00
TIME FIRST OBS(SEC PAST EPOCH): 389102348.816000 (2012-04-30 23:59: 8.82)
TIME LAST OBS(SEC PAST EPOCH) : 389188748.816000 (2012-05-01 23:59: 8.82)
NUMBER OF DATA RECORDS          :    82416
PRODUCT CREATE START TIME(UTC): 2012-06-25 15:06:18.000
PRODUCT CREATE END TIME(UTC)  : 2012-06-25 15:29:18.000
FILESIZE (BYTES)                :  3299112
FILENAME                        : AOD1B_2012-05-01_X_05.asc
PROCESS LEVEL (1A OR 1B)        : 1B
PRESSURE TYPE (SP OR VI)        : VI
MAXIMUM DEGREE                  : 100
COEFFICIENT ERRORS (YES/NO)     : NO
COEFF. NORMALIZED (YES/NO)      : YES
CONSTANT GM [M^3/S^2]           :  0.39860044150000E+15
CONSTANT A [M]                  :  0.63781364600000E+07
CONSTANT FLAT [-]               :  0.29825765000000E+03
CONSTANT OMEGA [RAD/S]          :  0.72921150000000E-04
NUMBER OF DATA SETS             : 16
DATA FORMAT (N,M,C,S)           : (2(I3,X),E15.9,X,E15.9)
END OF HEADER
DATA SET 01:   5151 COEFFICIENTS FOR 2002-05-01 00:00:00 OF TYPE atm
  0   0 -.666624533E-10 0.000000000E+00
  1   0 0.190851967E-09 0.000000000E+00
…
100  99 0.358595920E-13 -.775798222E-13
100 100 -.232602751E-13 -.428385882E-13
DATA SET 02:   5151 COEFFICIENTS FOR 2002-05-01 00:00:00 OF TYPE glo
  0   0 -.666624533E-10 0.000000000E+00
  1   0 -.134104180E-09 0.000000000E+00
...
100  99 0.476333557E-13 -.706918867E-13
100 100 -.471617805E-13 -.410401989E-13
DATA SET 03:   5151 COEFFICIENTS FOR 2012-05-01 00:00:00 OF TYPE oba
  0   0 0.495506969E-09 0.000000000E+00
  1   0 0.667669143E-11 0.000000000E+00
...
100  99 0.707426096E-14 -.632682187E-14
100 100 -.593949867E-14 0.962139597E-14
DATA SET 04:   5151 COEFFICIENTS FOR 2012-05-01 00:00:00 OF TYPE ocn
  0   0 -.111022302E-15 0.000000000E+00
  1   0 -.324956147E-09 0.000000000E+00


...

DATA SET 13:   5151 COEFFICIENTS FOR 2012-05-01 18:00:00 OF TYPE atm
  0   0 -.698412439E-10 0.000000000E+00
  1   0 0.186100398E-09 0.000000000E+00
...
100  99 0.371270413E-13 -.844661759E-13
```

```
100 100 -.249752352E-13 -.383175966E-13
DATA SET 14:   5151 COEFFICIENTS FOR 2012-05-01 18:00:00 OF TYPE glo
  0   0 -.698412439E-10 0.000000000E+00
  1   0 -.655994406E-10 0.000000000E+00
...
100  99 0.484388333E-13 -.899935159E-13
100 100 -.505244072E-13 -.389103461E-13
DATA SET 15:   5151 COEFFICIENTS FOR 2012-05-01 18:00:00 OF TYPE oba
  0   0 0.579448711E-09 0.000000000E+00
  1   0 0.367351372E-10 0.000000000E+00
...
100  99 0.343878180E-14 -.165026313E-13
100 100 -.993987841E-14 0.104389398E-13
DATA SET 16:   5151 COEFFICIENTS FOR 2012-05-01 18:00:00 OF TYPE ocn
  0   0 0.000000000E+00 0.000000000E+00
  1   0 -.251699838E-09 0.000000000E+00
.
100  99 0.113117920E-13 -.552733997E-14
100 100 -.255491720E-13 -.592749436E-15
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6. References

General References on Atmosphere and Ocean De-aliasing

Case K., Kruizinga, G., Wu, S.; GRACE Level 1B Data Product User Handbook; JPL Publication D-22027, 2002

Fagiolini, E., L. Zenner, F. Flechtner, T.Gruber, G. Schwarz, T. Trautmann und J. Wickert (2007). The Sensitivity of Satellite Gravity Field Determination to Uncertainties in AtmosphericModels. In: Joint GSTM / SPP Kolloquium, Potsdam.

Farrel W.E.; Deformation of the Earth by Surface Loads; Review of Geophysics, Vol. 10, p. 761-797, 1972

Foldvary L., Fukuda Y.; IB and NIB Hypotheses and Their Possible Discrimination by GRACE, Geophysical Research Letters, Vol.28, No. 4, p. 663-666, 2001.

Gegout P., Cazenave A.; Temporal Variations of the Earth Gravity Field for 1985-1989 derived from Lageos; Geophysical Journal International, Vol. 114, p. 347-359, 1993

Heiskanen W.A., Moritz H., Physical Geodesy; W.H. Freeman Publications Co., San Francisco, 1967

Pekker T.; Comparison of the Influence of Real Vertical Mass Distribution in the Atmosphere versus Surface Pressure Representing Atmospheric Mass on Time Dependent Gravity; Internal Report Center for Space Research at University of Texas in Austin, 2001.

Persson A.; User Guide to ECMWF Forecast Products; Meteorological Bulletin M3.2, ECMWF, 2000

Ponte R., Ali, A.H.; Rapid ocean signals in polar motion and length of; Geophysical Research Letters, Vol. 29, Articel 1711, 2002

Ponte R., Gaspa P.; Regional Analysis of the Inverted Barometer Effect over the Global Ocean Using TOPEX/POSEIDON Data and Model results; Journal of Geophysical Research, Vol. 104, No. C7, p. 15587-15601, 1999

Ponte, R., Ray, R .: Atmospheric pressure corrections in geodesy and oceanography: A strategy for handling tides, Geophys. Res. Lett., 29(24), L2153, doi: 10.1029/2002GL016340, 2002.

Schrodin R. (Ed.); Quarterly Report of the Operational NWP-Models of the DeutscherWetterdienst; No. 22, Dec. 1999- Feb. 2000

Swenson S., Wahr J.; Estimated Effects of the Vertical Structure of Atmospheric Mass on the Time-Variable Geoid; Paper submitted to Journal of Geophysical Research – Solid Earth, 1999

Vedel H.; Conversion of WGS84 Geometric Heights to NWP Model HIRLAM Geopotential Heights; Danish Meteorlogical Institute – Scientific Report 00-04, 2000

Velicogna, I., Wahr, J., Van den Dool, H.; Can Surface Pressure be used to remove atmospheric contributions from GRACE data with sufficient accuracy to recover hydrological signals?; Journal of Geophysical Research, Vol. 106, No. B8, p. 16415-16434, 2001

White P.W. (Ed.); IFS Documentation Part III: Dynamics and Numerical Procedures (CY21R4); ECMWF Research Department, 2001

References on Baroclinic Ocean Model OMCT

Accad, Y., and C.L. Pekeris, Solution of the tidal equations for the M_2 and S_2 tides in the world oceans from a knowledge of the tidal potential alone, Phil. Trans. R. Soc. London Ser. A, 290, 235-266, 1978.

Arakawa, A., and V.R. Lamb, Computational design of the basic dynamical processes of the UCLA general circulation model, Meth. Comput. Phys., 17, 173-265, 1977.

Dobslaw, H., Modellierung der allgemeinen ozeanischen Dynamik zur Korrektur und Interpretation von Satellitendaten, Sci. Techn. Rep. 04/07, GFZ Potsdam, available at http://ebooks.gfz-potsdam.de/pubman/item/escidoc:8750:3/component/escidoc:8749/0710.pdf, 2007.

Dobslaw, H., and M. Thomas, Atmospheric induced ocean tides from ECMWF forecasts, Geophys. Res. Lett., 32, L10615, 2005.

Dobslaw, H., and M. Thomas, Simulation and observation of global ocean mass anomalies. J. Geophys. Res., 112, C05040, 2007.

Dobslaw, H., Flechtner, F., Bergmann-Wolf, I., Dahle, Ch., Dill, R., Esselborn, S., Sasgen, I., and M. Thomas, Simulating High-Frequency Atmosphere-Ocean Mass Variability for De-Aliasing of Satellite Gravity Observations: AOD1B RL05, J. Geophys. Res., 118, 10.1002/jgrc.20271, 2013.

Beljaars, A.C.M., Air-sea interaction in the ECMWF model, ECMWF seminar proceedings on: Atmosphere-surface interaction, 8-12 September 1997, p. 33-52, Reading, 1997.

Chambers, D.P., Wahr, J., Nerem, R.S., Preliminary observations of global ocean mass variations with GRACE, Geophys.Res. Lett., 31, L13310, doi:10.1029/2004GL020461, 2004.

Drijfhout, S., C. Heinze, M. Latif, and E. Maier-Reimer, Mean circulation and internal variability in an ocean primitive equation model, J. Phys. Oceanogr., 26, 559-580, 1996.

Greatbach, R.J., A note on the representation of steric sea level in models that conserve volume rather than mass, J. Geophys. Res., 99, 12,767-12,771, 1994.

Gross, R.S., I. Fukumori, and D. Menemenlis, Atmospheric and oceanic excitation of the Earth's wobbles during 1980-2000, J. Geophys. Res., 108(B8), 2370, doi: 10.1029/2002JB002143, 2003.

Hellerman, S., and M. Rosenstein, Normal monthly wind stress over the world ocean with error estimates, J. Phys. Oceanogr., 13, 1093-1104, 1983.

Hibler III, W.D., A dynamic thermodynamic sea ice model, J. Phys. Oceanogr., 9, 815-846, 1979.

Levitus, S., Climatological atlas of the world ocean, NOAA Professional Paper, 13, 173 pp., U.S. Department of Commerce, 1982.

Ponte, R.M., and D. Stammer, Global and regional axial ocean angular momentum signals and length-of-day variations (1985-1996), J. Geophys.Res., 105, 17,161-17,171, 2000.

Thomas, M., Ocean induced variations of Earth´s rotation – Results from a simultaneous model of global circulation and tides, Ph.D. diss., 129 pp., Univ. of Hamburg, Germany, 2002.

Thomas, M., and H. Dobslaw, On the impact of baroclinic ocean dynamics on the Earth's gravity field, Proceedings Joint CHAMP/GRACE Science Team Meeting, Potsdam, 2004, available at http://edoc.gfz-potsdam.de/gfz/get/13998/0/af144247702d6833d9d85b994e36fe01/13998.pdf

Wolff, J.O., E. Maier-Reimer, and S. Legutke, The Hamburg Ocean Primitive Equation Model HOPE, Technical Report No. 13, DKRZ, Hamburg, 103pp, 1996.

Wünsch, J., M. Thomas, and T. Gruber, Simulation of oceanic bottom pressure for gravity space missions, Geophys. J. Int., 147, 428-434, 2001.

7. Acronyms

AOD1B	Atmosphere and Ocean De-aliasing Level-1B Product
ECMWF	European Centre for Medium Weather Forecast
DWD	Deutscher Wetterdienst
GFZ	GeoForschungsZentrum Potsdam
GRACE	Gravity Recover And Climate Experiment
ISDC	Integrated System and Data Center
NCEP	National Center for Environmental Predictions
OCN1B	Ocean level-1B product
OMCT	Ocean Model for Circulation and Tides
PO.DAAC	Physical Oceanographic Distributed Active Archive Center
PPHA	barotropic ocean model code: name termed after its main developers Pacanowski, Ponte, Hirose and Ali